WELL DRILLING PRACTICES

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PB Energy Storage Services, Inc.

July, 2016

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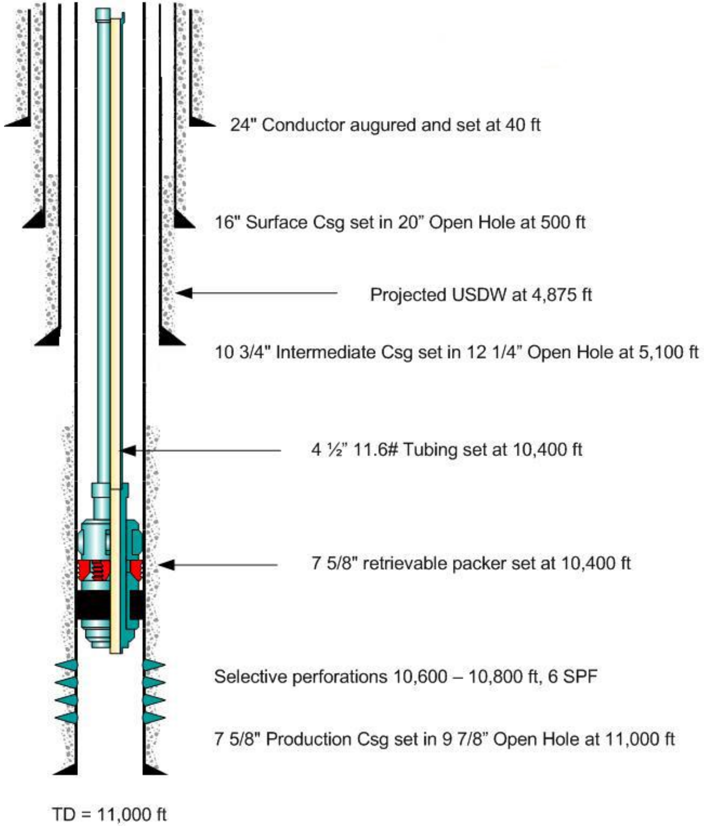
GAS STORAGE WELL DESIGN

Integrity Comes First



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GAS STORAGE WELL DESIGN

General Design Issues

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- Casing Design
  - Mechanical Integrity of well
  - Cost considerations
  - Set limits on operating conditions
  - Satisfy regulatory requirements
- Casing Evaluation
  - New pipe
  - Currently installed pipe
- Cement Types
  - Portland Cements
  - Epoxy Resins
- Cement Evaluation
  - Traditional cement bond logs
  - Ultrasonic radial and flexural attenuation logs

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GAS STORAGE CASING DESIGN

Design Factors and Safety Factors

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A “Design Factor” for a particular size and grade of casing is defined as the minimum ratio between a casing rating from API 5C2 and the estimated casing load.

$$DF = \frac{Casing\ Rating}{Planned\ Load} \geq DF_{\ (\mathrm{min})}$$

The casing rating is found in API bulletin 5C2 and is based on a formula found in API bulletin 5C3 (corrected to take into account the effects of corrosion, wear and fatigue).

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GAS STORAGE CASING DESIGN

Design Factors and Safety Factors

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A “Safety Factor” is the result of applying the Design Factor in the loading calculations in order to impart a degree of confidence that the design is fit for purpose. A safety factor of 1.0 is the minimum standard for a project.

Design Considerations

- Casing setting depths
- Fluid evacuation
- Buoyancy
- Expected pressures
- Mud weight
- Cement weight
- Fracture gradients
- Fluid compositions
- Directional profile
- Temperature

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Design Factors and Safety Factors

IV. CASING

TYPE	INTERVAL (MD)	HOLE SIZE	PURPOSE	CONDITION
20"	0'-50'	24"	Conductor	Contractor Discretion
13-3/8" , 48#/ft, H40	0'-550'	17-1/2"	Surface New	
8-5/8", 24#/ft, J55	0'-4,200'	12-1/4"	Intermediate	New
5-1/2", 15.5#/ft, L80	0-10,000'	7-7/8"	Production	New

CASING DESIGN SAFETY FACTORS

TYPE	TENSION	COLLAPSE	BURST
13-3/8" , 48#/ft, H40	7.88	4.63	3.72
8-5/8", 24#/ft, J55	1.59	1.09	1.01
5-1/2", 15.5#/ft, L80	1.28	1.19	1.54

DESIGN CRITERIA AND CASING LOADING ASSUMPTIONS

SURFACE CASING – (13-3/8")

Tension: A 1.8 design factor utilizing the effects of buoyancy (9.2 ppg).

Collapse: A 1.125 design factor with full internal evacuation and a collapse force equal to the mud gradient in which the casing will be run (0.47 psi/ft). The effects of axial load on collapse will be considered.

Burst: A 1.1 design factor with a surface pressure equal to the fracture gradient at setting depth. Internal burst force at the shoe will be cement hydrostatic pressure at that depth. No backup pressure or effects of tension on burst are utilized.

INTERMEDIATE CASING – (8-5/8")

Tension: A 1.8 design factor utilizing the effects of buoyancy (10.2 ppg).

Collapse: A 1.125 design factor with 50% internal evacuation and a collapse force equal to the mud gradient in which the casing will be run (0.53 psi/ft).

Burst: A 1.1 design factor with an internal burst force at the shoe equal to the fracture pressure at that depth. Back pressure will be formation pore pressure. The effects of tension on burst will not be utilized.

PRODUCTION CASING – (5-1/2")

Tension: A 1.8 design factor utilizing the effects of buoyancy (9.0 ppg).

Collapse: A 1.125 design factor with full internal evacuation and a collapse force equal to the mud gradient in which the casing will be run (0.48 psi/ft). The effects of axial load on collapse are considered.

Burst: A 1.1 design factor with a anticipated maximum tubing pressure (5,000 psig) on top of the maximum anticipated packer fluid (diesel) gradient (0.37 psi/ft). Back pressure on production string will be formation pore pressure (0.433 psi/ft). The effects of tension on burst will not be utilized.

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GAS STORAGE WELL DESIGN

Casing Evaluation

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New casing or tubing

Many companies have approved vendor lists for casing and other oilfield tubular goods (OTG) sourcing.

- Steel mills located in the following geographic areas are generally approved:
  - *North America*
  - *Western Europe (no previous Communist Block Countries)*
  - *South Africa*
  - *Japan*
  - *South Korea*

- Mill Test Reports (MTR's) are required
- For new pipe with MTR's, usually the only other evaluation is to clean threads, drift the pipe, and manually inspect before going in the hole.

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GAS STORAGE WELL DESIGN

Casing Evaluation

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Currently Installed Pipe

Once the casing has been installed and cemented in place, or has been in the hole for many years, additional tests may be run periodically to test integrity

- Mechanical integrity tests – chart and record annular pressure integrity
- Run well logs to determine casing thickness or other anomalies (usually must pull tubing to expose the casing for analysis).
  - Multi fingered calipers
  - Casing inspection logs
  - Noise logs
  - Temperature logs

- If tubing is removed from hole, it can be inspected manually or replaced.

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GAS STORAGE WELL CEMENT

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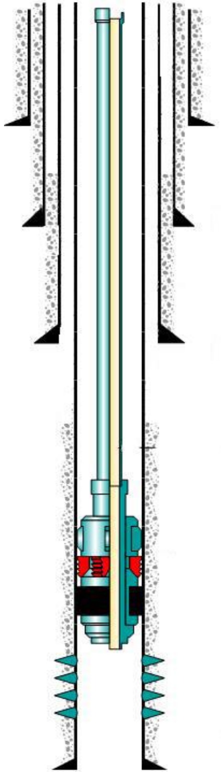
Casing Cement

- Cement is used to form a bond between the casing and the borehole, support the casing, and seal the annulus
- Most traditional oilfield cements generally don't have a lot of strength because they have to be thinned out into a "slurry" and pumped through small annular spaces for long distances.
- In many instances, cements are not required to be pumped to the surface around intermediate or production casing.
- In areas where there is no cement, casing can be exposed to saline waters and the exterior can become corroded over time.



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GAS STORAGE WELL CEMENT

Portland Cements

- Portland Cements are a blend of limestone and clay.
- API Specification 10A lists 8 typical classes of oilfield cements. (A thru H)

    - Different cement classes will generally be used depending on the depths and temperatures they will be exposed to.
    - Classes may also be differentiated by the downhole conditions they are subject to (primarily sulfate or other corrosive environments).
    - Most common are
        - Class C – generally used at shallow depths where fast setup times are needed.
        - Class G or Class H – can withstand higher downhole temperatures, have slower setup times.

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Resin Cements

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Resin Cement

- Relatively new epoxy based resin cements are being used more frequently in hostile environments and squeeze operations
- These types of cements have much higher compressive and shear strengths and can be used as the primary cement or pumped into very small annular spaces for squeeze jobs.

HALLIBURTON

WellLock® Resin

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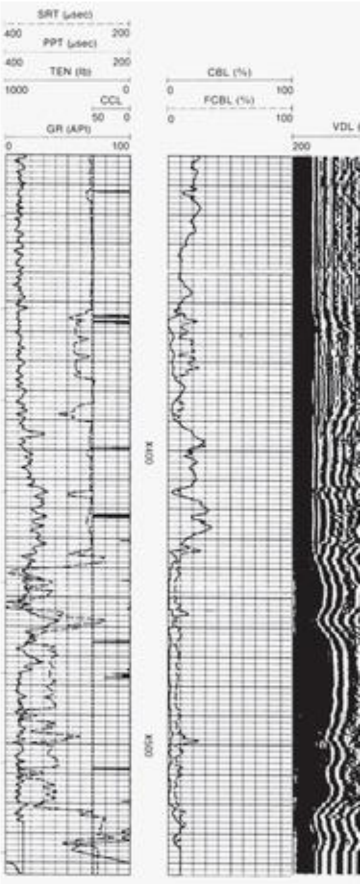
CEMENT EVALUATION TOOLS

Traditional Cement Bond Logs vs Radial and Flexural Attenuation Logs

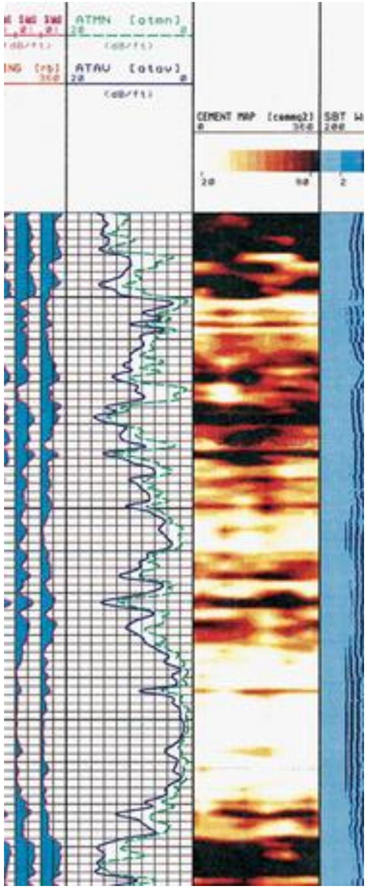
- Traditional (acoustic) cement bond logs do not measure cement quality.
  - CBL's measure the degree of "bonding" between the casing and the borehole by generating acoustic waves between transmitters and receivers and measuring the received amplitude of the sonic wave.
  - The higher the amplitude (imagine a bell ringing), the more "free" the pipe is.
  - Conversely, the lower the amplitude, the more bonded the pipe is to the borehole.



CEMENT EVALUATION TOOLS

Traditional Cement Bond Logs vs Radial and Flexural Attenuation Logs

- Radial (ultrasonic) cement bond logs look at different areas of the pipe simultaneously.
  - Radial logs display a “map” of the casing as if it were cut open and folded flat.
  - The tool measures the impedance of the ultrasonic signal for each area of investigation.
  - The higher the impedance the better the bond to the pipe.
  - Good for showing microannuli and channeling of cement behind pipe.
  - Also shows casing thickness



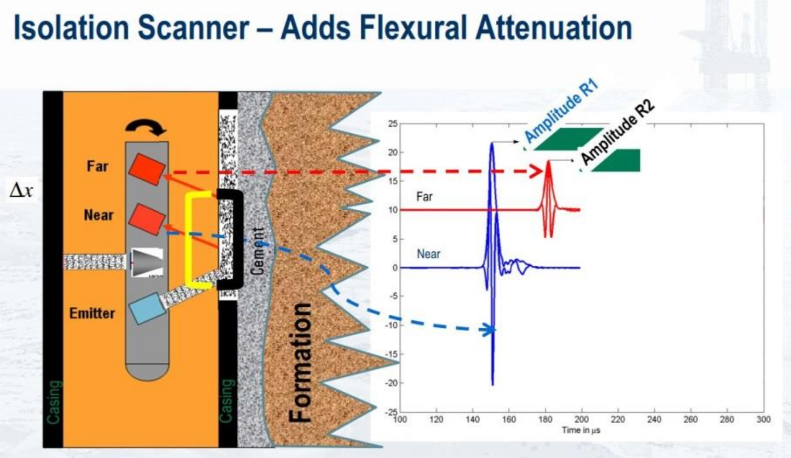
CEMENT EVALUATION TOOLS

Traditional Cement Bond Logs vs Radial and Flexural Attenuation Logs

Flexural attenuation logging tools

- Advanced tools now measure the flexural attenuation of the casing. FA is a function of the impedance contrast between the inner and outer walls of the casing. The decay of the flexural wave is also driven by the fluid in contact with the inner casing as well as the cement (if present) in contact with the outer casing.

- Schlumberger's technology uses acoustic waves to measure FA and can even spot the "third interface" which is an indication of the bond between the cement and the formation.



Schlumberger

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CEMENT EVALUATION TOOLS

Traditional Cement Bond Logs vs Radial and Flexural Attenuation Logs

Flexural attenuation logging tools

- Baker Hughes new Integrity Explorer (INTEX) tool measures FA using electromagnetic pulses from pad contact devices mounted on the sonde.
- One of the advantages with this tool is the ability to log without fluid in the hole.
- Even though Schlumberger and Baker Hughes measure FA differently, the technology employed helps to overcome the difficulty of logging in lightweight (or epoxy resin) cements where the attenuation of the signal makes interpretation difficult.

BAKER HUGHES

WELL DRILLING PRACTICES

Summary

- Casing Design
  - Integrity starts with good casing design
  - Design Factors and Risk Factors should be documented for new wells, and estimated for old wells.
  - Risk may increase when certain variables are unknown or legacy data has been lost

- Casing Evaluation
  - Know your pipe sources and get good records from trusted mills
  - Use casing evaluation logs to establish casing integrity

- Cement Types
  - Older wells probably used traditional Portland cements for the majority of their drilling programs.
  - If it is established that additional cement will improve integrity of the well, the use of epoxy resin cements are becoming more popular for tight squeeze jobs.

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WELL DRILLING PRACTICES

Summary

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- Cement Evaluation
  - Traditional cement bond log records may be adequate for identification of well integrity
  - Ultrasonic radial and flexural attenuation logs are becoming more popular when questions from traditional bond logs can't be answered.

- Record Keeping
  - Keep all records of the work that has been done on the well! Original logs, drilling and workover reports, MIT's, well tests, permits etc. are all important. Digitize and enter them in a document management system for faster retrieval.
  - Management of storage field integrity requires a systematic approach that includes not just analyses of drilling and workover risk, but analyses of risks of all sorts.
    - Reservoir
    - Wellbore
    - Surface

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QUESTIONS??

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